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THE 8 O'CLOCK ARC: A SERENDIPITOUS DISCOVERY OF A STRONGLY LENSED LYMAN BREAK GALAXY IN THE SDSS DR4 IMAGING DATA

Sahar S. Allam[1,2], Douglas L. Tucker[1], Huan Lin[1], H. Thomas Diehl[1], James Annis[1], Elizabeth J. Buckley-Geer[1], Joshua A. Frieman[1,3]

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ABSTRACT

We report on the serendipitous discovery of the brightest Lyman Break Galaxy (LBG) currently known, a galaxy at $z = 2.73$ that is being strongly lensed by the $z = 0.38$ Luminous Red Galaxy (LRG) SDSS J002240.91+143110.4. The arc of this gravitational lens system, which we have dubbed the "8 o'clock arc" due to its time of discovery, was initially identified in the imaging data of the Sloan Digital Sky Survey Data Release 4 (SDSS DR4); followup observations on the Astrophysical Research Consortium (ARC) 3.5m telescope at Apache Point Observatory confirmed the lensing nature of this system and led to the identification of the arc's spectrum as that of an LBG. The arc has a spectrum and a redshift remarkably similar to those of the previous record-holder for brightest LBG (MS 1512-cB58, a.k.a "cB58"), but, with an estimated total magnitude of $(g,r,i) = (20.0,19.2,19.0)$ and surface brightness of $(\mu_g,\mu_r,\mu_i) = (23.3,\ 22.5,\ 22.3)$ mag arcsec^{-2}, the 8 o'clock arc is thrice as bright. The 8 o'clock arc, which consists of three lensed images of the LBG, is $162°(9.6'')$ long and has a length-to-width ratio of 6:1. A fourth image of the LBG — a counter-image — can also be identified in the ARC 3.5m g-band images. A simple lens model for the system assuming a singular isothermal ellipsoid potential yields an Einstein radius of $\theta_{\rm Ein} = 2.91'' \pm 0.14''$, a total mass for the lensing LRG (within the 10.6±0.5 h^{-1} kpc enclosed by the lensed images) of $1.04\times10^{12}h^{-1}M_\odot$, and a magnification factor for the LBG of $12.3^{+15}_{-3.6}$. The LBG itself is intrinsically quite luminous ($\approx 6 \times L_*$) and shows indications of massive recent star formation, perhaps as high as 160 $h^{-1}M_\odot$ yr^{-1}.

Subject headings: gravitational lensing — galaxies: high-redshift

1. INTRODUCTION

Strongly lensed galaxies are particularly useful for studies of galaxy evolution due to the magnification of the galaxy magnitude: since surface brightness is conserved by lensing, the stretching of the galaxy shape increases the apparent brightness of the source galaxy. These apparently brighter objects are then prime candidates for detailed follow-up studies at a fraction of the telescope time that would be necessary for comparable but unlensed galaxies.

If a strongly lensed galaxy also happens to be a Lyman Break Galaxy (LBG), so much the better. LBGs are galaxies in which the low-flux region of the spectrum blueward of the Lyα Hydrogen line at 1216Å has been redshifted into the U band; LBG samples thus provide a vital window into the galaxy populations of the high redshift ($z > 2.7$) Universe (e.g., Adelberger et al. 1998, 2003; Steidel et al. 1998; Giavalisco et al. 1998). LBGs, however, are generally rather faint, and detailed studies of these high-redshift galaxies profit from the additional magnification provided for by strong lensing (Nesvadba et al. 2006).

Previously, just two examples of strongly lensed LBGs have been discovered: MS1512-cB58 at $z = 2.7$ (a.k.a, "cB58"; Yee et al. 1996, Teplitz et al. 2000, Pettini et al. 2002, Baker et al. 2004) and the 1E0657-56 arc+core at $z = 3.2$ (Mehlert et al. 2001). A search by Bentz et al. (2003) using the Sloan Digital Sky Survey Early Data Release (SDSS EDR; Stoughton et al. 2002) yielded six bright ($r \sim 20$) candidate LBGs with $z = 2.45 - 2.80$, but these were later found to be unlensed bright quasars (Ivison et al. 2005).

Here, we report on the serendipitous discovery in the SDSS data of the brightest case of these rare objects, a strongly lensed $z = 2.73$ LBG which we have nicknamed the "8 o'clock arc".

This letter is organized as follows: § 2 describes the initial discovery in the SDSS imaging data, § 3 describes the confirmatory followup imaging and spectroscopy, and § 4 describes modeling and comparison with previously known high redshift LBGs. § 5 contains discussion and § 6 concludes. Throughout, we assume a flat cosmology with $\Omega_{\rm m} = 0.3$, $\Omega_\lambda = 0.7$, and $H_0 = 100h$ km s^{-1} Mpc^{-1}, unless otherwise noted.

2. THE INITIAL DISCOVERY

The SDSS (York et al. 2000) is a digital imaging and spectroscopic survey that, over the course of five years, has mapped nearly one quarter of the celestial sphere in five filter bands ($ugriz$; Fukugita et al. 1996) down to $r = 22.2$ and has obtained spectra for $\approx 10^6$ astronomical objects (Adelman-McCarthy et al. 2007) . Although the SDSS completed its first phase of operations in June 2005, a three-year extension known as SDSS-II is in progress. (For more details on SDSS-II, please consult `www.sdss.org`.)

To explore the effects of interactions on the properties of galaxies in different environments, Allam et al. (2004) extracted a catalog of interacting/merging galaxy pairs

[1] Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510
[2] University of Wyoming, Dept. of Physics & Astronomy, P.O.Box 3905, Laramie, WY 82071
[3] Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637

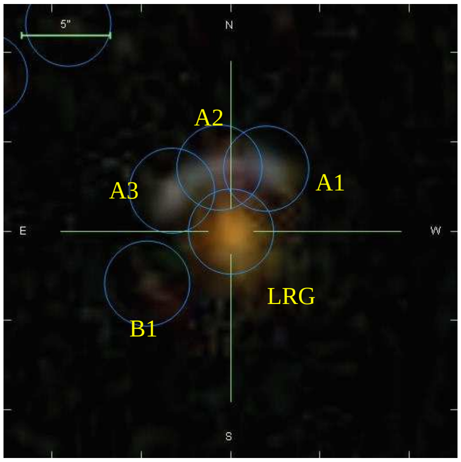

FIG. 1.— SDSS *gri* color image showing the location of three lensed images (A1, A2, A3), the position of the LRG, and a faint back ground LRG (B1) at photometric redshift of 0.53.

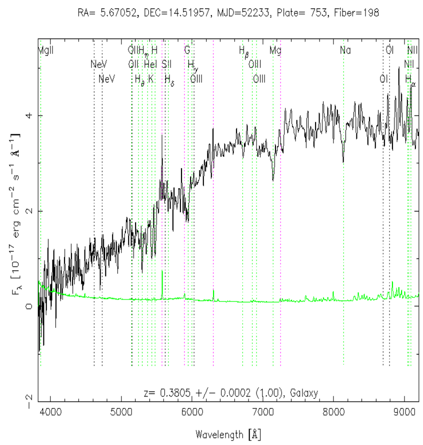

FIG. 2.— The SDSS spectrum for the LRG SDSS J002240.91+143110.4.

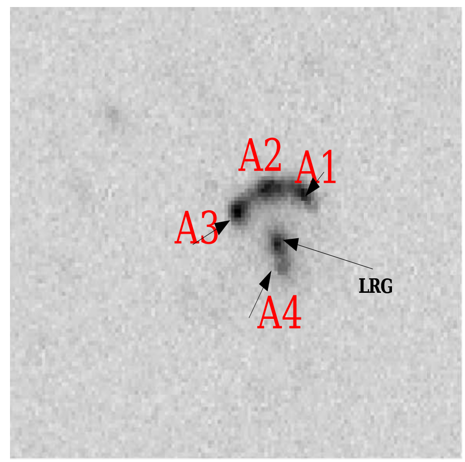

FIG. 3.— The coadded ARC 3.5m SPICAM *g*-band image clearly shows the three components of the arc (A1, A2, A3) as well as the counter image (A4); the center of the LRG is also marked.

from the SDSS imaging data. During visual inspection of a new version this catalog (Allam et al. 2007) based upon the SDSS DR4 (Adelman-McCarthy et al. 2006) imaging data, a very unusual merging galaxy pair with a galaxy-galaxy separation of 4.02″was discovered (see Fig. 1). The two components of this system are SDSS J002240.91+143110.4, which is a Luminous Red Galaxy (LRG), and SDSS J002240.78+143113.9, which is a very blue and elongated object. The SDSS targeted SDSS J002240.91+143110.4 (hereafter, "the LRG"; for LRG selection, cf. Eisenstein et al. 2001) with a 3″spectroscopic fiber. The resulting spectrum (Fig. 2) shows absorption features of an early type galaxy at redshift of z=0.38 with Ca H and K lines at 5463 and 5510Å. The very blue and elongated SDSS J002240.78+143113.9 was not targetted for SDSS spectroscopy and hence has no SDSS spectrum.

Allam recognized this system as a probable gravitational lens and, due to its time of discovery, dubbed it the "8 o'clock arc." The arc is a very blue high surface brightness object north of the LRG, subtending an angle of ≈162°about the galaxy.

The arc consists of three components, which are the blue A1 (SDSS J002240.78+143113.9) the reddish blue A2 (SDSS J002240.96+143113.9), and the blue A3 (SDSS J002241.14+143112.7). The arc containing these three components extends over 9.6″in length and has a length to width ratio of 6:1.

3. THE CONFIRMATION

In order to confirm the identification of the system as a gravitational lens, we carried out follow-up imaging and spectroscopy on the Astrophysical Research Consortium (ARC) 3.5m at Apache Point Observatory on the night of 2006 August 24 (UT).

3.1. *Imaging*

The imaging was obtained under photometric conditions and with a seeing of 1.0–1.2″ (FWHM) during the first half of the night. The instrument used was the SPIcam CCD imager, which has a field-of-view of $4.78' \times 4.78'$. Three exposures of 300 sec each were obtained in each of the SDSS *gri* filters; a 15″ dithering pattern about the LRG was employed.

The resulting images were processed using the IRAF `ccdred` package. The images were then co-added with the `swarp` package (Bertin 2000, v2.16; see Fig. 3), and object detection and measurement were made with `SExtractor` (Bertin & Arnouts 1996). We used a weighted coaddition, accounting for flux scaling between the images, and aperture photometry with an aperture of 3″. Photometric zeropoints were derived by matching objects detected in the co-added images with objects in the SDSS imaging data and comparing their `SExtractor` `MAG_AUTO` instrumental magnitudes with their SDSS model magnitudes. The *gri* magnitudes measured from these co-added images are listed in Table 1. An astrometric solution for the coadded images was measured relative to the SDSS overlapping bright stars in the field of view.

3.2. *Spectroscopy*

Slit spectroscopy was carried out with the DIS III (Dual Imaging Spectrograph) using the standard Medium Red/Low Blue grating setup during the second half night of night. Six exposures were obtained under moon-less conditions for a total exposure time of 140 min. The seeing was 1″–1.2″ (FWHM). A slit width of 1.5″was employed, and the slit was oriented to cover as much of the three components of the 8 o'clock arc as was possible. The standard Medium Red/Low Blue grating setup covers an effective spectral range of 3600Å to 9600Å at a linear resolution of 2.43″pix^{-1} in the blue part

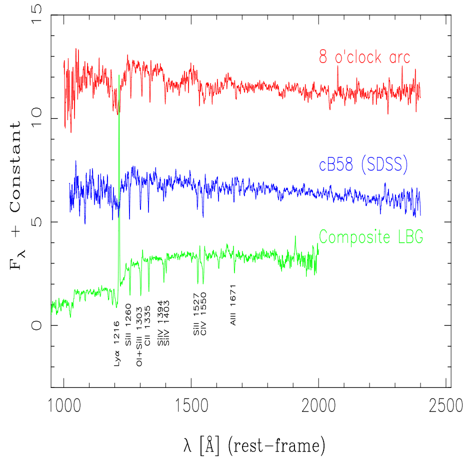

FIG. 4.— The discovery spectrum taken with the DIS-III spectrograph on the ARC 3.5m telescope is plotted in red. The SDSS spectrum of cB58, a strongly lensed L_* LBG at z = 2.72, is plotted in blue, and a composite LBG spectra (Shapley et al. 2003) in green. Several important absorption lines are marked.

of the spectrum and $2.26''$pix^{-1} in the red; the spatial scale is $0.4''$pix^{-1}. HeNeAr lamp exposures were taken for wavelength calibration. The HST spectrophotometric standard G191-B2B was observed for flux calibration.

The spectra were reduced using the IRAF `ccdred` package and the `doslit` task. The six individual spectroscopic exposures of the 8 o'clock arc were combined using the `scombine` task, and the red and blue spectra were spliced together using the `spliceSpec` task from Gordon Richard's `distools` external IRAF package.

The redshift of the 8 o'clock arc was estimated to be $z = 2.73$ based on measurements of Lyα λ 1215.7, SiII λ1260.4, OI+SiII λ(1302.2+1304.4), CII λ1334.5, SiIV λ1393.8, SiIV λ1402.8, SiII λ1526.7, CIV+CIV λ1549.5, and AlII λ1670.8, confirming that the arc is indeed a gravitational lens. Figure 4 shows the spectrum of the 8 o'clock arc and, for comparison, the SDSS-measured spectrum of the former "brightest known LBG" (cB58), and an LBG composite spectra from Shapley et al.(2003).

Both cB58 at $z = 2.72$ and the 8 o'clock arc at $z = 2.73$ show damped Lyα, along with the typical stellar and instellar absorption lines found in LBGs, quite similar to those visible in the composite spectrum.

4. THE LENS MODEL

We began with a simple mass model to reconstruct the lensing plane. We used the pixel positions of the three lensed images and the counter image in the coadded SPIcam g band images as measured by `SExtractor`, since the counter image (A4) is not resolved in either the r or i band coadded images. The measured positions are shown as blue triangles in Figure 5. We then assumed a singular isothermal ellipse (SIE), and used the `gravlens/lensmodel` software of Keeton (2001) to perform fits; the resulting fitted position are plotted in Figure 5 as open boxes. The best fit SIE model yields an Einstein radius of $\theta_{\rm Ein} = 2.91'' \pm 0.14''$, or $R_{\rm Ein} = 10.6 \pm 0.5 h^{-1}$ kpc. The best fit χ^2 is 2.1 for NDF=7, where we assumed positional errors of $\pm 0.1''$.

Since both the redshift of the LRG and the LBG are known we were able to determine the angular diameter distance to the source (D_s), to the lens (D_l), and between the source and lens (D_{sl}), to be 1141, 752 and 863 h^{-1} Mpc, respectively. The total magnification was found to be a factor of $12.3^{+15}_{-3.6}$ ($\gtrsim 4$ for each of the three arc images). The velocity dispersion of the mass distribution doing the lensing was predicted to be 391 ± 19 km s^{-1}, which is large but not unprecedented for an elliptical galaxy. (E.g., Crampton et al. 2002 modelled a velocity disperson of 387$\pm$5 km s^{-1} for the strongly lensed elliptical galaxy CFRS 03.1077, and Bernardi et al. 2006 find $\sim$50 galaxies with $\sigma > 350$ km s^{-1} from a SDSS sample of 39,320 elliptical galaxies.)

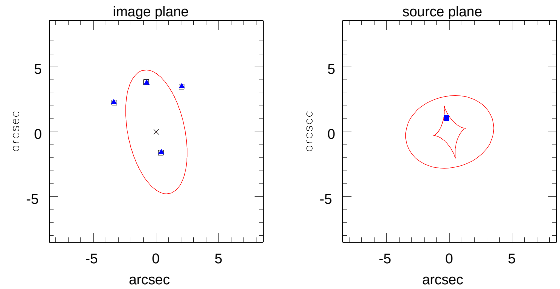

FIG. 5.— The results of fitting an SIE model. In the left plot the measured postions are shown as blue triangles, the fitted positions are the open boxes and the cross represents the lensing galaxy. In the right plot the blue square represents the postion of the source. The critcal curves and caustics are shown in red.

The fitted ellipticity and position angle are 0.53 ± 0.06 and $12° \pm 2°$, respectively. These fitted values agreed well within 1σ with the observed values for these parameters for the LRG in the SDSS DR4 database (0.46 and 12°, respectively).

From this simple SIE model we can determine the mass interior to $R_{\rm Ein}$ using $M_{\rm Ein} = (c^2/4G)(D_l D_s/D_{sl}) \times \theta^2_{\rm Ein}$. We find that $M_{\rm Ein} = 1.04 \times 10^{12} h^{-1} M_\odot$. As we know the lens distance we can determine the mass-to-light ratio and we find a value of $16 h M_\odot/L_\odot$ (i-band).

5. DISCUSSION

The spectrum of the 8 o'clock arc (Fig. 4) shows that the lensed source galaxy is an LBG, albeit an uncommonly bright one: lensed, it is 4.6 mag brighter (g-band) than an L_* LBG (Adelberger & Steidel 2000). Even after accounting for a lensing magnification of ≈ 12.3 (§ 4), the 8 o'clock arc is 1.9 mag ($\approx$ a factor of 6) more luminous than L_* for LBGs.

For comparison, cB58 is a typical L_* LBG lensed by the large $z = 0.37$ foreground cluster MS 1512+36 (Yee et al. 1996). Furthermore, cB58 is magnified by a factor of ~ 30 and has an apparent brightness only about one-third that of the 8 o'clock arc (Seitz et al. 1998). We also note that the relative simplicity of the environment surrounding the 8 o'clock arc's lensing LRG permits a quite robust determination of the lensing amplification, whereas the lensing amplification for cB58 is rather sensitive to the assumed cluster mass distribution model.

We can also estimate the star formation rate of the 8 o'clock arc LBG using a scaling relation given in Pettini et al (2000). The relation is given for cB58 but for the accuracy necessary here we can take cB58 and the 8 o'clock arc to be at the same redshift: SFR $= 3 \times 37 \times (\frac{30}{f_{lens}}) \times (\frac{f_{dust}}{7}) \times (\frac{2.5}{f_{\rm IMF}}) M_\odot {\rm yr}^{-1}$ where the additional factor of 3 over the Pettini et al. relation (their eq. [6]) takes into account the fact the 8 o'clock arc's total apparent brightness is roughly three times that of cB58. For the 8 o'clock arc, $f_{lens} = 12.3$ and we take the other parameters to be the same, leading to SFR $= 270 M_{\odot}\mathrm{yr}^{-1}$ ($H_0 = 70$ km s^{-1} Mpc^{-1} and q_0=0.1), or SFR $= 160 h^{-1} M_{\odot}\mathrm{yr}^{-1}$ ($\Omega_{\mathrm{m}} = 0.3$, $\Omega_{\lambda} = 0.7$). This should be taken as an estimate only, as the Pettini et al. relation is based upon UV continuum luminosity and gives the highest of all the star formation rate estimates for cB58. Followup measurements of the 8 o'clock will provide more detailed rate estimates. Taking the estimate at face value, the 8 o'clock arc is in the top 20% of star formation rates given for LBGs in Shapley et al. (2001).

Understanding the environment of the LRG and the lensed LBG is critical for interpreting the results of the gravitational lens modeling. Therefore, we have run maxBcg cluster finder (Koestler et al. 2006) on the area. The LRG sits near a maxBcg cluster, with a center at $(\alpha,\delta)_{\mathrm{J2000}} = (5.6749°, 14.5003°)$ and a photometric redshift of $z_{\mathrm{photo}} = 0.384$ and richness $N_{gals} = 21$. This is a reasonably massive cluster, and the lensing LRG sits just 260 kpc from the brightest cluster galaxy. This may give an additional sheet surface mass contribution to the lensing, but it is likely that this is a very small effect (Kochanek, private communication).

6. CONCLUSIONS

We have reported on the discovery of a strongly lensed LBG at a redshift of $z = 2.73$, the arc of which we have named the "8 o'clock arc." At an apparent magnitude of $(g,r,i) = (19.95, 19.22, 18.98)$, it displaces cB58 as the brightest known LBG by over a magnitude.

The arc consists of three lensed images of the LBG and subtends a length of $162°(9.6'')$ around the the lensing galaxy, an early type galaxy at $z = 0.38$. The length-to-width ratio of the arc is 6:1. A fourth (counter) image is also visible in the co-added ARC 3.5m g-band image.

A simple SIE lens model for the system yields an Einstein radius of $\theta_{\mathrm{Ein}} = 2.91'' \pm 0.14''$ ($R_{\mathrm{Ein}} = 10.6 \pm 0.5$ h^{-1} kpc), a total lensing mass within the Einstein radius of $1.04 \times 10^{12} h^{-1} M_{\odot}$, and a magnification factor for the LBG of $12.3^{+15}_{-3.6}$. Based upon this model's value for the magnification factor, it is clear that the LBG is not only apparently bright but also quite intrinsically luminous (about $6 \times L_*$). Furthermore, a simple scaling relation from Pettini et al. (2000) indicates that the LBG may be experiencing an episode of vigorous star formation, perhaps as high as 160 $h^{-1} M_{\odot}$ yr^{-1}. The remarkably low apparent magnitude of this object makes it an ideal object for further followup with more detailed observations.

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These results are based on observations obtained with the Apache Point Observatory 3.5-meter telescope, which is owned and operated by the Astrophysical Research Consortium.

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TABLE 1
APO 3.5m SDSS Photometry.

ID	ra (2000.0)	dec (2000.0)	g‡	r‡	i‡
LRG	00:22:40.91	14:31:10.0	20.14	18.62	18.16
A1	00:22:40.79	14:31:13.8	21.18	20.21	20.13
A2	00:22:40.97	14:31:14.0	20.99	20.40	20.11
A3	00:22:41.15	14:31:12.6	21.27	20.68	20.21
B1	00:22:41.44	14:31:06.8	23.67	23.02	22.40
Arc total mag			19.95	19.22	18.96
Arc μmag arcsec^{-2}			23.26	22.54	22.28
A4	00:22:40.89	14:31:08.9	∼22	···	···

‡The estimated magnitude error is ±0.1 mag. The magnitudes listed have not been corrected for instellar extinction, which is 0.22 mag, 0.16 mag, and 0.12 mag, for g, r, and i, respectively (Schlegel et al. 1998).

REFERENCES

Adelberger, K. L., Steidel, C. C., Giavalisco, M., Dickinson, M. E., Pettini, M., & Kellogg, M. 1998, ApJ, 505, 18
Adelberger, K. L., & Steidel, C. C. 2000, ApJ, 544, 218
Adelberger, K. L., Steidel, C. C., Shapley, A. E., & Pettini, M. 2003, ApJ, 584, 45
Adelman-McCarthy, J. K., et al. 2006, ApJS, 162, 38
Allam, S. S., Tucker, D. L., Smith, J. A., Lee, B. C., Annis, J., Lin, H., Karachentsev, I. D.,& Laubscher, B. E. 2004, AJ, 127, 1883
Allam, S. S., et al. 2007, in prep.
Baker, A. J., Tacconi, L. J., Genzel, R., Lutz, D., & Lehnert, M. D. 2004, ApJ, 613, L113
Bernardi, M., et al. 2006, AJ, 131, 2018
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bertin et al. 2000 swarp
Bentz et al. 2004, ApJL, 600, L19
Crampton, D., Schade, D., Hammer, F., Matzkin, A., Lilly, S. J., & Le Fèvre, O. 2002, ApJ, 570, 86
Dickinson, M., et al. 2004, ApJ, 600, L99
Eisenstein, D. J., et al. 2001, AJ, 122, 2267
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Giavalisco, M., Steidel, C. C., Adelberger, K. L., Dickinson, M. E., Pettini, M., & Kellogg, M. 1998, ApJ, 503, 543
Ivison et al. 2005, MNRAS, 362, 535
Keeton, C. R. 2001, astro-ph/0102340
Koestler et al. 2006,(submitted/astroph)
Mehlert, D., et al. 2001, A&A, 379, 96
Nesvadba, N. P. H., et al. 2006, preprint (astro-ph/0606527)
Pettini, M., Steidel, C. C., Adelberger, K. L., Dickinson, M., & Giavalisco, M. 2000, ApJ, 528, 96
Pettini, M., Rix, S. A., Steidel, C. C., Adelberger, K. L., Hunt, M. P., & Shapley, A. E. 2002, ApJ, 569, 742
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Shapley, A. E., Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., & Pettini, M. 2001, ApJ, 562, 95
Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, ApJ, 588, 65
Seitz, S., Saglia, R. P., Bender, R., Hopp, U., Belloni, P., & Ziegler, B. 1998, MNRAS, 298, 945
Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., Pettini, M., & Kellogg, M. 1998, ApJ, 492, 428
Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1
Stoughton, C., et al. 2002, AJ, 123, 485
Teplitz, H. I., et al. 2000, ApJ, 533, L65
Yee, H. K. C., Ellingson, E., Bechtold, J., Carlberg, R. G., & Cuillandre, J.-C. 1996, AJ, 111, 1783
York, D. G., et al. 2000, AJ, 120, 1579